WBS 1.2 – Booster Upgrades

A set of upgrades are needed to increase the delivery of protons from the Booster. The most direct improvements are achieved by reducing beam losses, and increasing the repetition rate.

WBS 1.2.1 – Booster RF Duty Cycle Limits

Once the improvements outlined in this section are implemented, all Booster systems will be capable of operating at a sustained 15 Hz repetition rate. At that point, rate limitations will come from the RF system. The repetition rate limit is believed to be about 8-9 Hz and involves three key issues:

- While it has been determined that the feeder which supplies the RF system is adequate for 15 Hz operation, there is currently a limit from the 1000 kVA transformer which acts as a substation.
- Half of the "bias supplies", which control the resonant frequency of the RF cavities, have output transformers that are not capable of 15 Hz operation.
- The pulse modulators, which modulate the on-cavity power amplifiers (PA's), contain some rather antiquated subcomponents which become unreliable at high repetition rate.

The first two issues result in rather hard limits to the repetition rate. Part of this task is to determine that limit and develop a plan and a rough cost estimate to ameliorate the situation. Whether or not this plan is implemented will be a matter for further discussion.

The issue of the modulators is somewhat more problematic. Rather than presenting a hard repetition rate limit, it has been found that the modulators become progressively more unreliable as repetition rate is increased. This is already becoming apparent at our present repetition rate. Part of this task involves determining the specific failure issues in the modulators and developing a plan for addressing these. The actual plan will be implemented under WBS 1.2.13.

WBS 1.2.2 – ORBUMP System

The Booster uses H- ion injection so that beam can be injected over several revolutions. A system of four pulsed magnets forms a chicane that moves the circulating and injected beams radially, such that they lie on top of one another at injection. The two then pass through a foil to strip the electrons from the ions, after which they circulate together. This system is referred to as "ORBUMP".

There are two problems to be addressed with the ORBUMP system:

- Both the magnets and the power supply suffer from internal heating, limiting the total average repetition rate to roughly 7.5 Hz.
- The system is not powerful enough to fully align the circulating beam with the injected beam. This results in horizontal mismatch of approximately 1 cm, which significantly increases beam loss at injection.

Approximately half of the beam loss in the Booster occurs very early in the cycle. This is due largely to beam slewing caused by the ORBUMP system. Improving this situation is a crucial part of the plan.

The new plan not only includes new magnets and a new power supply, but a new injection scheme which will allow the injection bump to operate with only three magnets rather than four and eliminate one additional injection element. This new scheme will, however, require a rearrangement of the 400 MeV injection line which was not originally envisioned.

Figure 2.1 shows the injection scheme as it is now. The H- beam enters at 13° to the beam and is steered by a rather powerful magnet so that it is parallel to the circulating beam. It then goes through the first two magnets of the injection bump, which together with the circulating beam, at which point both pass through a stripping foil and begin to circulate together.

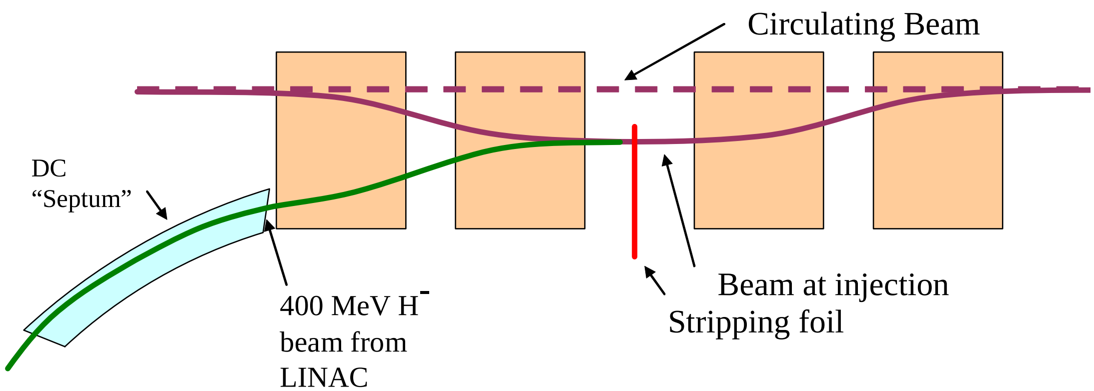


Figure 2.1: Schematic view of present Booster ion injection.

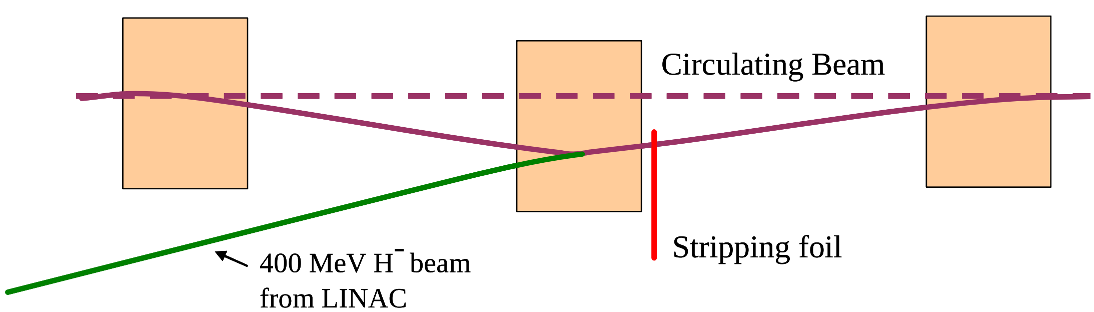


Figure 2.2: Modified Booster injection scheme.

The new scheme is shown in Figure 2.2. The DCSEP element has been eliminated, and now there are only three bump magnets, the outer two running at half the current of the middle one. Because the whole arrangement has been stretched out, this means that the central magnet is running at roughly the same current that all four magnets were operating at before. The injected beam comes in at 3.5° relative to the circulating beam, which is just enough to clear the upstream lattice magnet. This requires significant rearrangement of the 400 MeV injection line, as shown in Figure 2.3, but does not introduce any elements; in fact eliminates one of the horizontal bend magnets.

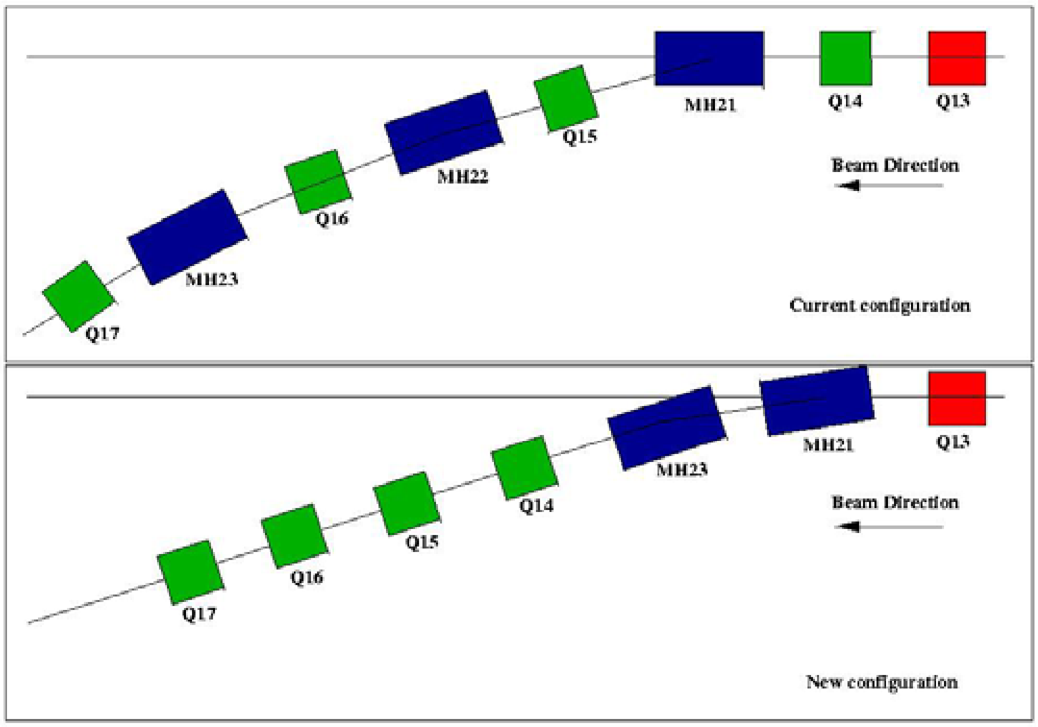


Figure 2.3: Schematic view of the 400 MeV line rearrangement. The shallower injection angle results in the elimination of one horizontal bend element. The existing quadrupoles will be rearranged.

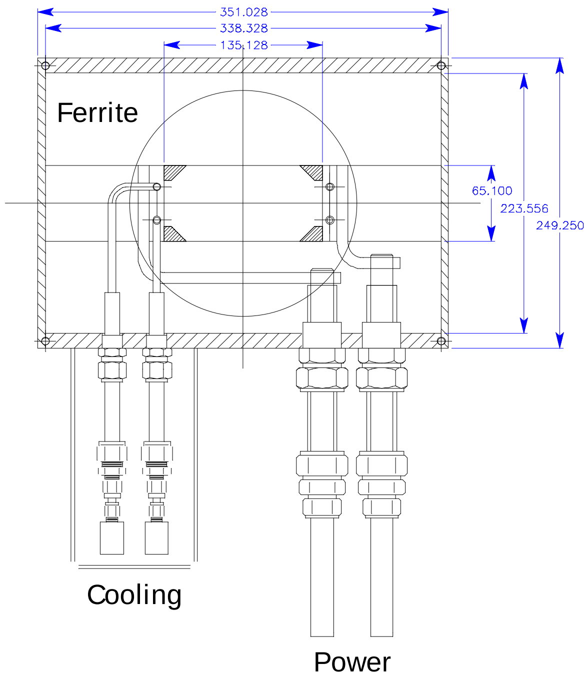


Figure 2.4: Cross section of the magnet. Cooling channels allow for the cooling of the conductors.

Details of the magnet design can be found elsewhere [cite: FERMILAB-CONF-05-119-AD-TD]. The magnets themselves are based on ferrite, which does not suffer the thermal issues associated with laminated magnets. Figure 2.4 shows a cross-section of the magnet and Table 2.1 shows the magnet parameters.

$\int B\,dl$ @ 15 kA	0.1676 Tesla Meters
Inductance	1.83 uHenry
Resistance	< 1 mOhm
Width	13.51 cm
Height	6.51 cm
Length	52.33 cm

Table 2.1: Magnetic parameters of the new ORBUMP magnets.

In the strip line design, the outer two magnets are connected in parallel and then put in series with the central magnet. It should be noted in passing that this arrangement insures that even if there are slight impedance mismatches, the net dipole moment will always be zero. Nevertheless, the strip line design has the two parallel legs passing through a toroid in opposite directions, thus allowing us to directly measure any current mismatch. All of this represents a significant improvement over the current system. Because of the reduced current, the strip line will not require water cooling, which also simplifies the design.

Parameter	**Specification**
Nominal Pulse Amplitude	15 kA
Peak Pulse Amplitude	17.5 kA
Maximum Flat Top Duration	50 μs
Flatness	±0.5%
Minimum Rise Time	30 μs
Maximum Rise Time	40 μs
Minimum Fall Time	30 μs
Maximum Fall Time	40 μs
Repetition Rate	15 Hz
Repeatability	±1%
Undershoot Amplitude	<5%
Undershoot Duration	<10 μs

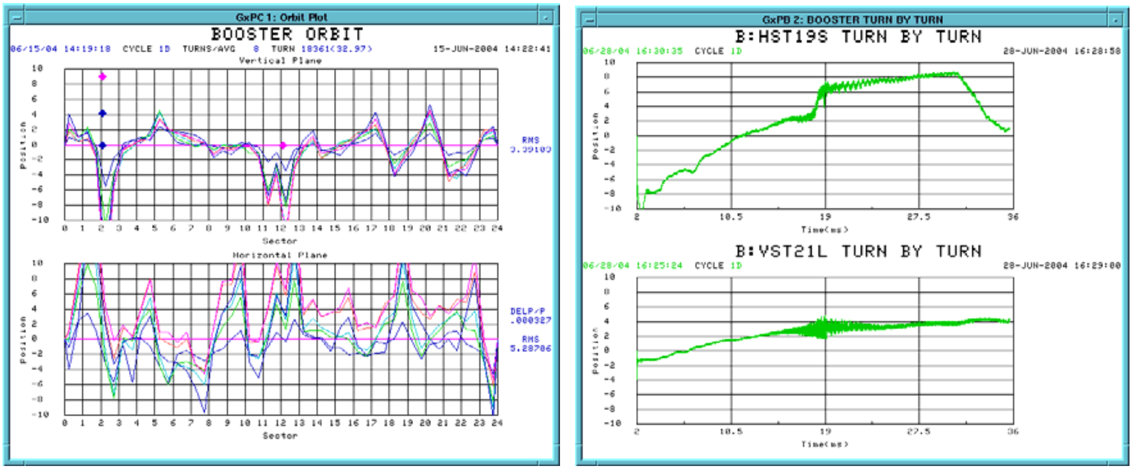
Table 2.2: Specifications for ORBUMP power supply.

The power supply has been designed to meet the specifications in Table 2.2. It is functionally identical to the existing supply and will in fact use the same tunable inductors in the pulse forming network (PFN). It will, however, use new capacitors which are capable of pulsing indefinitely at 15 Hz. The SCR switch network was originally designed to be used in the existing power supply. The charging supply and controls are more or less identical to those used on the power supplies for the MP01 and MP02 extraction septa.

WBS 1.2.3 – Corrector System

The Booster has a corrector system comprised of horizontal and vertical trim dipoles as well as regular and skew quadrupoles in each of the 48 sub-periods. Unfortunately, this system has never been powerful enough to control either the beam position or tune at high field. Figure 2.5 shows the beam motion during the acceleration cycle.

This motion leads to beam loss throughout the cycle. By having a corrector system capable of fully controlling the orbit, we will be able to reduce this loss significantly. This requires a corrector system capable of approximately 1 cm of beam motion at all energies.



(a) (b)

Figure 2.5: Beam position (mm) through the Booster cycle: (a) the orbit around the ring at several times in the cycle, relative to the injected orbit, (b) two selected locations as a function of time throughout the cycle. This beam motion was used to specify the new corrector packages.

In addition to problems from beam motion, the Booster suffers from other inadequate control of the beam. In particular, the quadrupole trims cannot control the beam tune throughout the cycle. Also, the existing corrector packages do not contain sextupole correctors. We currently do chromaticity correction at discrete locations around the ring. This introduces harmonic content which can lead to instabilities. Finally, our existing magnets do not have the slew rate capability sufficient to control the beam at transition.

The proposed replacement correctors are described in detail elsewhere [cite: FERMILAB-CONF-05-164-AD-TD]. The specifications are shown in Table 2.3.

The proposed replacement corrector is shown in Figure 2.6. It consists of twelve poles, which are wound to produce six specific multi-pole fields: vertical dipole, horizontal dipole, quadrupole, skew quadrupole, sextupole, and skew sextupole.

In the existing corrector scheme, the correctors are positioned next to BPM's at each sub period. In order to allow the maximum length for the new correctors, the BPM has been integrated into the design.

New power amplifiers are needed to drive the current ramp profiles. Higher currents and voltages are specified in order to provide the higher magnet fields and faster slew rates. A draft specification for the power amplifiers has been written for the purpose of estimating project schedule and costs, and identifying vendors that could possibly provide the power amplifiers needed [cite:BEAMS-DOC-1881-V1]. In order to power the six different coils in each of the forty-eight corrector packages, two hundred and eighty-eight new power amplifiers will need to be procured.

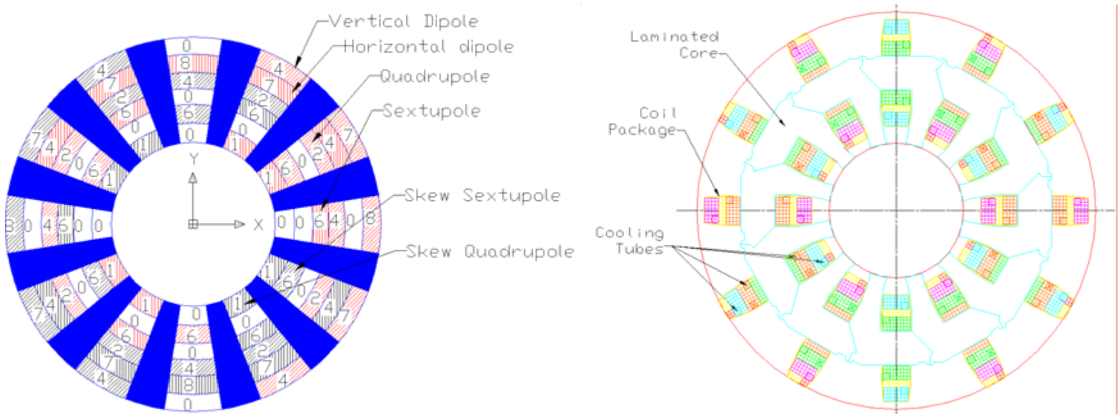


Figure 2.6: New Booster corrector design. Twelve poles are wound in such a way as to produce six discrete multi-pole fields, as is shown schematically on the left. On the right is shown the details of the windings along with the cooling channels. There are two distinct types of racetrack coils wound on a laminated core.

Type	Integrated field or gradient	Aperture field or gradient	Field, T at 25.4mm radius
Horizontal dipole	0.009 T-m	0.045 T	0.045
Vertical dipole	0.015 T-m	0.075 T	0.075
Normal quadrupole	0.08 T	0.4 T/m	0.01016
Skew quadrupole	0.008 T	0.04 T/m	0.001016
Normal sextupole	1.41 T/m	7.05 T/m^2	0.00455
Skew sextupole	1.41 T/m	7.05 T/m^2	0.00455

Table 2.3: Specifications for new Booster Correctors

CAMAC power supply controllers have been specified and design considerations are being made by the AD/Controls department in order to provide these modules. The modules will need to generate the programmable voltage curves that are used as the reference curves to the power amplifiers to produce the current ramp profiles. These modules will also measure the current monitor outputs of the power amplifiers to compare to the reference curves to ensure that the power amplifiers are producing the desired current ramps. Digital outputs for enabling and disabling the amplifiers, as well as amplifier status read back will also be provided. The current version of the specification for this module is given in [cite: Beams-doc-1882-V1].

Racks and power cables are needed for housing the new power amplifiers and connecting power to the corrector packages. Rack space and penetrations for routing the power cable from the gallery into the booster enclosure has been identified. Figure 2.7 shows a Booster floor plan which has been marked up to show the location of the new corrector magnets, the location of the new racks, and possible routing of power cables [cite:BEAMS-DOC-1883]. The new racks are laid out in six groups. Each group supports one sixth of the booster correctors; that is, eight corrector packages, forty eight power amplifiers. An approximate layout of the racks is given in the Figure 2.8. The red rectangles represent the power amplifiers.

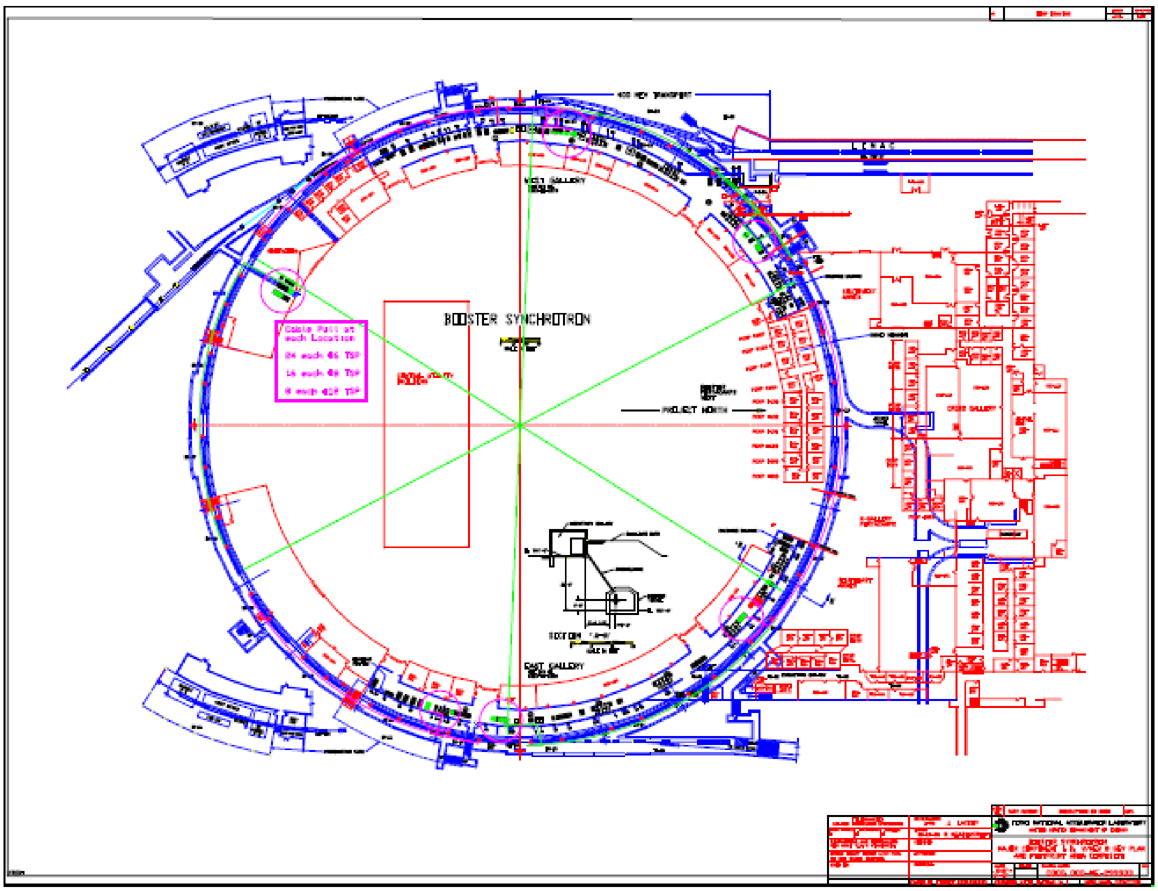


Figure 2.7: Booster layout, marked up to show the locations of the new corrector magnets (red dots), the location of the new racks (green rectangles), and possible routing of power cables.

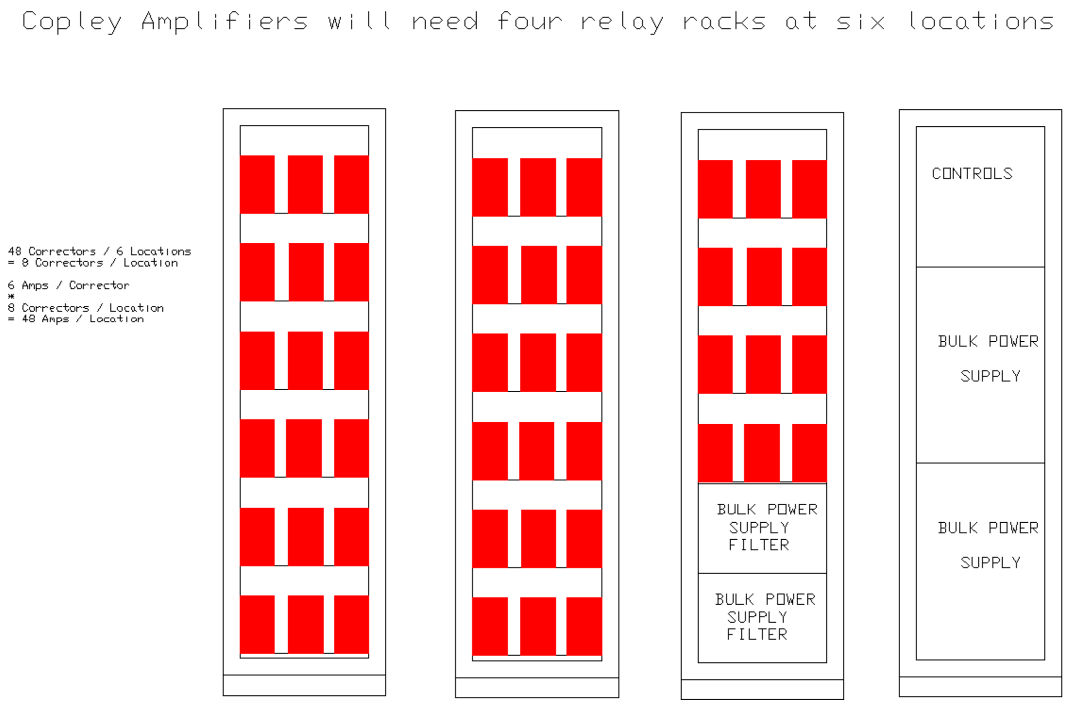


Figure 2.8: An approximate layout of the racks for the corrector system power supplies.

Estimates have been made with regard to the RMS currents that the power cables will need to support in order that appropriate wire gauges are used. The horizontal and vertical dipoles and the normal quadrupole are expected to use 6 AWG twisted shielded cable. The normal and skew sextupoles are expected to use 8 AWG twisted shielded cable. The skew quadrupole draws only a small current and is expected to use a 12 AWG twisted shielded cable. The available penetrations into the Booster are expected to be able to support all of these cables.

Unlike the present correctors, these will require cooling, so new plumbing will need to be installed in the Booster enclosure. The specifications are driven by the maximum power losses listed in Table 2.4.

Magnet Type	Coil Resistance (Ω)	Nominal Current (A)	Power Loss (W)
Vertical Dipole	0.27	49.6	665
Horizontal Dipole	0.27	29.7	238
Normal Quadrupole	0.166	42.5	300
Normal Sextupole	0.187	47.8	426
Skew Quadrupole	0.042	14.5	.6
Skew Sextupole	0.187	47.8	426

Table 2.4: Maximum power dissipation.

Each magnet will have two parallel water circuits. The total water flow will be about 1/2 GPM at 60 PSI water pressure drop. The water temperature rise will be about 20 C, when all magnets operate at the nominal current. The current water system in the Booster is expected to be able to handle this additional load.

The installation of the new plumbing is expected to be installed during the 2006 and 2007 shutdowns.

WBS 1.2.4 – 30 Hz Harmonic Upgrade

Simulations and studies have shown that the Booster intensity is limited by longitudinal bucket area. This will be accomplished by increasing RF voltage (WBS 1.2.8) and by decreasing the maximum acceleration rate.

The booster lattice magnets are not ramped in the usual sense. They are connected with a system of capacitors and inductors that form an offset 15Hz resonant circuit. The maximum dE/dt of the beam is fixed by the resonant frequency and the total acceleration, so reducing the maximum dE/dt will allow more beam to be accelerated. Modifying the circuit to add a properly phased 30 Hz component to the resonance [9] will extend the acceleration portion of the curve and reduce the maximum dE/dt. Figure 2.9 shows a potential reduction of 35% in the maximum acceleration.

The result of the 30 Hz harmonic will be an increase in the amount of beam that we can get through transition. We conservatively estimate an extra 0.5E12 per cycle.

The extra capacitors and inductors required will fit onto the existing magnet girders without significant modification. The gradient magnet power supplies (GMPS) will require some modification to allow the voltage to go negative, and the regulation software will require significant upgrade to properly control the two phases.

The cost estimate is determined from quotes for the choke and by general rules for the capacitors, based on their energy. Labor costs are included for prototyping, testing, final design, and a significant amount for installation. Estimates have been made for the cost of the GMPS modification and regulator software upgrade.

The plan is to prototype a complete girder during FY05, and to proceed with procurement as soon the design is finalized. The modification will cost approximately $1M (M&S) and will be installed during the 2006 shutdown.

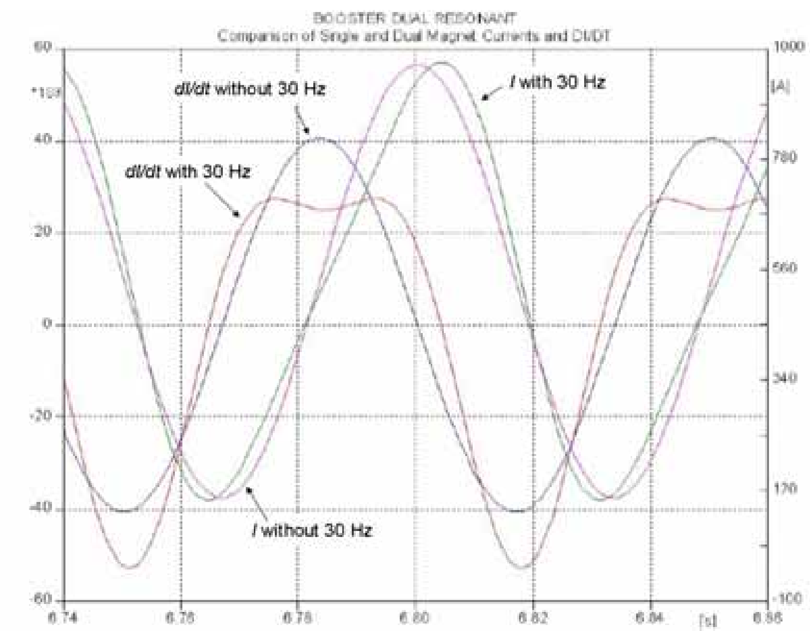


Figure 2.9: Effect of 30Hz component on the bend field in the Booster. Both the existing and modified waves are shown.

WBS 1.2.5 – Gamma-t System

The Booster "gamma-t" system [10] consists of 12 quadrupole magnets that can be pulsed when the beam is just below transition energy. The effect is to lower the transition energy below the energy of the beam so that longitudinal emittance blow-up is minimized.

This system has been in place for some time, but it suffers from two problems:

- The reduced longitudinal emittance exacerbates coupled-bunch oscillations after transition.
- The quadrupoles are not properly aligned, which causes significant closed orbit distortions when they are pulsed.

The first problem can now be ameliorated using the recently commissioned longitudinal damping system. The quadrupole misalignments can be calculated and corrected by studying the induced closed orbit distortions.

The initial part of this task involves a series of studies to determine the ultimate effectiveness of the gamma-t system. These should be completed by the end of 2005.

It has been determined that the existing magnets are not compatible with the corrector upgrade (1.2.3) in the short straight section. If the studies determine that a gamma-t system is warranted, then new pulsed magnets will be fabricated, which will be installed during the 2007 shutdown, along with the new correctors.

WBS 1.2.6 – Alignment Improvements-DESCOPED

There has been an ongoing program to improve Booster alignment for some time. Initially, we had envisioned combining all alignment initiatives into one task, but we ultimately decided that alignment more properly belonged under normal Booster operations, so this was removed from the Proton Plan.

WBS 1.2.7 – Booster RF Cavity Cooling

The original installation of the Booster RF drift tubes (DT) included stainless steel cooling lines connected to copper tubing on the inner DT surface. The cooling lines were found not to be necessary at low repetition rates and were disconnected. Inadequate cooling at high repetition rate (> 7.5 Hz) could cause failure of the custom ceramic blocking capacitors. We have started re-commissioning the cooling system with two stations completed in the 2004 shutdown and will incorporate this upgrade work into the cavity maintenance schedule. In the event that the 30+ year-old copper cooling lines leak, we will install a chill plate that serves the same function.

This task will be completed in Fall 2005.

WBS 1.2.8 – Booster RF Cavity #20-DESCOPED

Until recently the Booster operated with 18 RF stations installed, although there is space for 20 cavities. An R&D project in 2003-2004 built two large aperture cavities and installed the first in the 19th location to determine the benefit in lowering losses. Originally, we had planned to install a 20th cavity in the fall 2005 shutdown. Because this cavity would have required new support (modulator, bias supply, etc) hardware, the cost would have been significantly higher than the 19th, which was installed using spare support hardware.

At the time of this writing, the 19th cavity has not had a significant impact on Booster operations. For that reason, and in light of manpower limitations in the RF department, we have elected to descope the 20th RF cavity.

WBS 1.2.9 – Booster Solid State RF Upgrade

Traditionally, the highest maintenance components in the Booster are tubes in the cascode amplifier in the RF system. These are located in the tunnel, so servicing them is a problem given that the RF cavities can become activated. We are considering upgrading to a solid state system, more or less identical to the Main Injector. The potential benefits of such an upgrade are to reduce the maintenance costs, reduce technician radiation exposure and to improve reliability.

A cost/benefit and reliability analysis will be performed to determine whether a full or partial upgrade is warranted. The cost of the full upgrade is approximately $7M.

WBS 1.2.10 – Booster Instrumentation Upgrade-DESCOPED

Like the Linac instrumentation upgrades, it was decided that the Booster instrumentation upgrades were of a small enough scale that they should be handled as part of the normal Booster operating budget, so they have been removed from this plan.

WBS 1.2.11 – Booster Dump Relocation

The Booster currently has two extraction regions. In the third period is the primary extraction, which takes beam to the Main Injector and to the MiniBooNE experiment via the MI-8 beamline. The second extraction is in period 13, and was in fact the original extraction to the Main Ring. Now, it serves three purposes:

- When partial batches are extracted to the Main Injector, the remainder of the batch is extracted at period 13 to a dump.
- We are able to run test pulses to the dump, either between user cycles or when the Main Injector is in access.
- Beam can be steered to a dedicated Radiation Damage Facility (RDF) in this line.

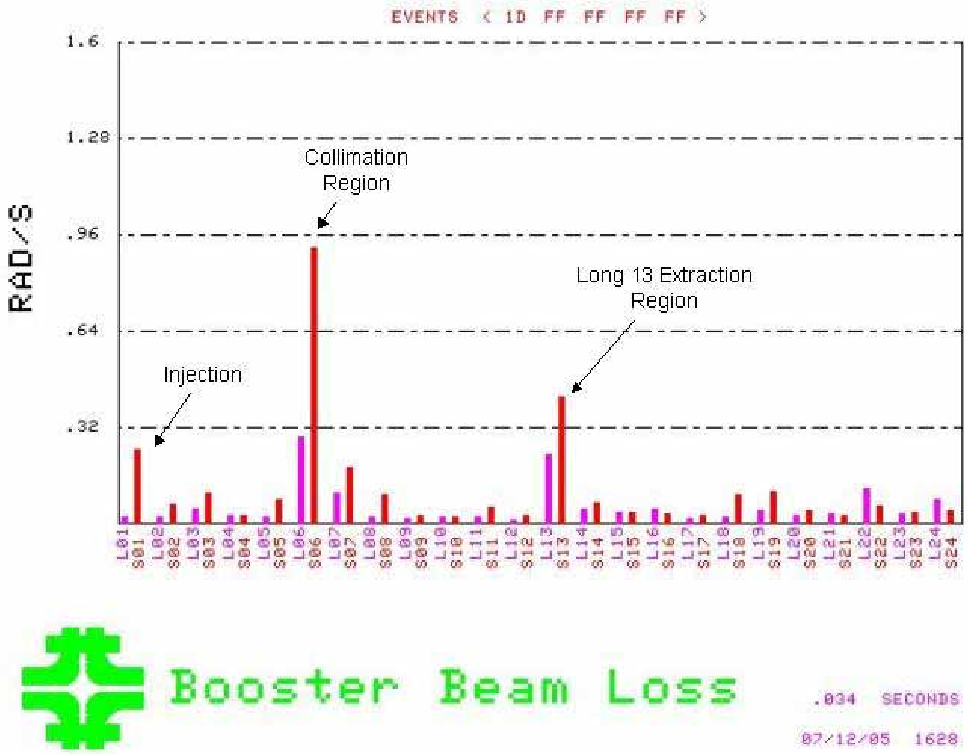


Figure 2.10: Beam loss pattern on a typical Booster cycle. It can be seen that the Long 13 extraction region represents a significant part of the uncontrolled loss.

In spite of attempts to improve the Booster lattice, period 13 remains a significant loss point, and results in constraints on beam control and Booster alignment. Figure 2.10 shows the un-normalized losses around the Booster for a typical cycle. The high losses in periods 6 and 7 are due to the collimation system, while the bulk of the remaining loss is near period 13.

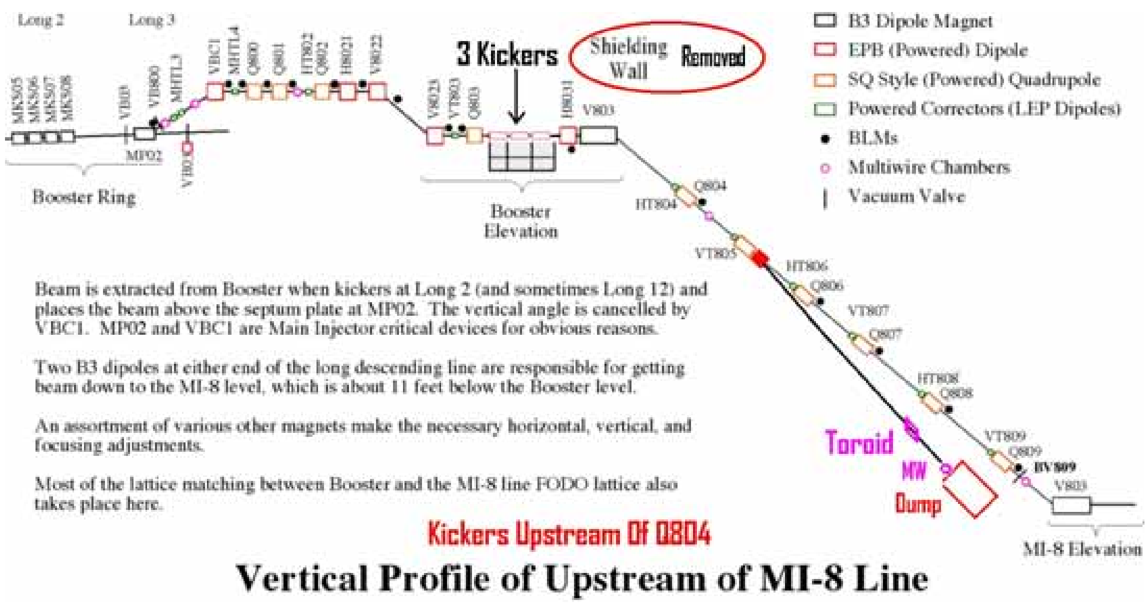


Figure 2.11: Schematic side view of the proposed extraction scheme. An existing shield wall is removed to provide space for three extraction kickers. An extraction septum is mounted just downstream of VT805.

For this reason, we have decided to eliminate the extraction at period 13 entirely and relocate it to the MI-8 line. The detailed scheme is shown in a side view in Figure 2.11. In the existing Long 3 extraction, the beam goes through a wall, which dates back to when it was used to send small numbers of protons to the antiproton ring. The wall is no longer needed, so in this scheme it is removed to provide space for three kickers, which will be relocated from Long 13. These will work together with an extraction septum located just down stream of the VT805 magnet in the MI-8 line. This septum would steer the beam downwards into a dump, located between the beam line and the floor.

In the Booster ring, each extraction region requires four stripline kickers, located one period upstream of the extraction septum. As part of this modification, the shielding wall in the MI-8 line will be dismantled, and three of the four kickers at period 12 will be moved to that location. Their associated power supplies will be relocated to the first floor of the Booster West Tower. This will leave one kicker and power supply at period 12, which can be timed to aid in the Long 3 extraction.

The Long 13 extraction septum is extremely radioactive, so for the time being, it will be left in the ring and merely raised out of the beamline. An identical spare will be used in MI-8, but the power supply will be moved from the East Booster Gallery to the West Booster tower to power it.

Beam will be extracted to a free standing dump which was used to commission the MI-8 and MI-12 beam lines.

Except for the removal of the shield wall, mechanical work in the tunnel is not significant. Stands will be designed and fabricated for the kickers, septum, and dump, and some miscellaneous beam pipe modifications will be made, but no other beam line elements will be moved.

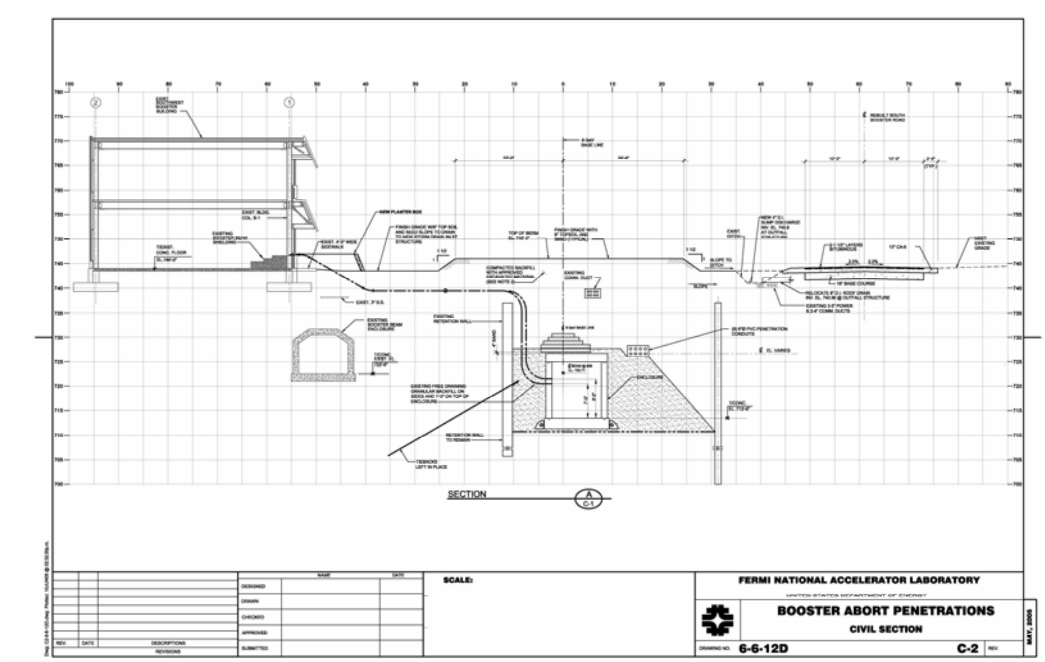


Figure 2.12: Conduit layout for MI-8 installation. Proposed conduits are shown as dotted lines.

Civil construction consists of eight 6” PVC conduits from the first floor of the Booster West Tower to the MI-8 tunnel, as shown in Figure 2.12.

A dedicated control rack will be placed near the new extraction septum power supply in the Booster West Tower. From the controls standpoint, this extraction will be essentially identical to extraction at period 13.

There is some residual field in the “field free region” near the conducting plane of the septum, which might affect the trajectory of the transmitted beam slightly. For this reason, the septum will be pulsed on every beam cycle so that this stray field can be compensated with DC correction elements. Whether or not beam is extracted will be controlled by the kickers. This is exactly how the system is currently operated at period 13.

WBS 1.2.12 – Booster Chopper

In order to reduce beam loss at extraction, a “notch” is created in the beam at injection energy. This is currently done with an extra kicker, which pulses long enough to kick about 4 of the 84 bunches into the collimation system. Unfortunately, this system was never designed to do this and the rise time and pulse quality are not really adequate. The result is a partial bunch in the gap that causes loss at extraction. We propose to build a new notcher, similar to the electrostatic chopper which is used to extract beam from the Linac to the Booster.

For the moment, this task has not been well scoped, and the cost estimate is based on similar devices built elsewhere.

WBS 1.2.13 – Booster RF Improvements

It has been found that running the Booster at high repetition rates results in reduced reliability of the RF system. Furthermore, Figure 2.13 shows a marked increase in Booster downtime over the last 10 years. The RF modulator units, many of which are over thirty years old, are prone to failure. We are investigating replacing the RF system with one based on solid state PA drivers (WBS 1.2.9). If approved, this will require new modulators and therefore will address this problem as a side benefit.

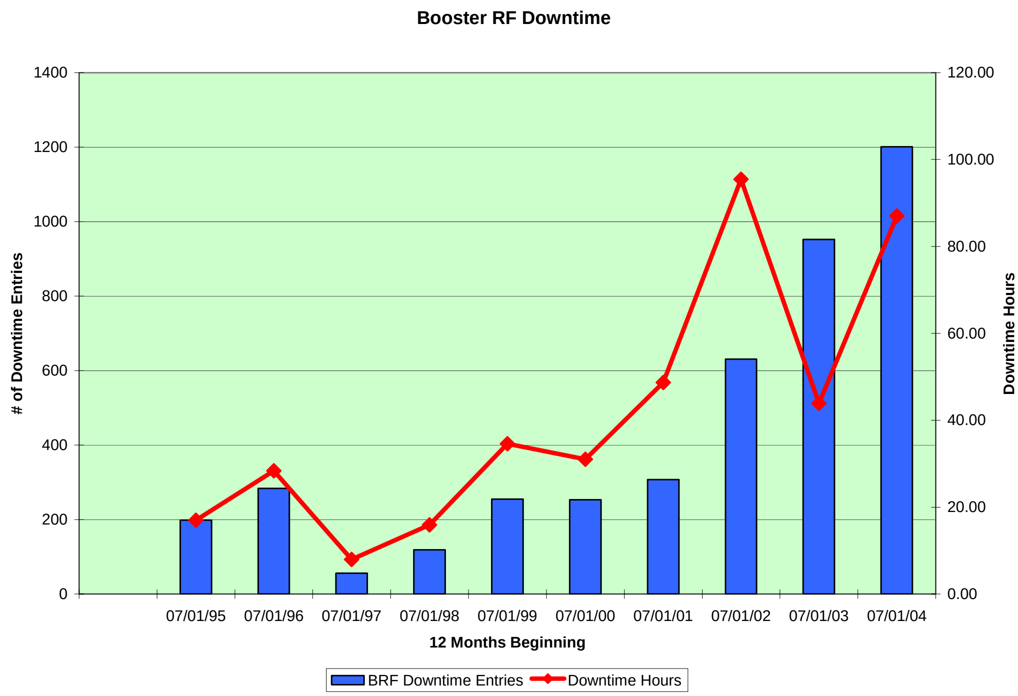


Figure 2.13: Booster downtime due to RF problems.

In the event that WBS 1.2.9 is de-scoped, we will proceed with this task to develop a program of major maintenance for the modulators to significantly improve their reliability. The general plan will be to cycle through the units on a regular maintenance schedule. Individual modulator units will be removed, serviced and replaced. We have allocated $50K per station for general upgrades of the units.